Bulletin of Earthquake Engineering (2006) 4:159–175
DOI 10.1007/s10518-006-9004-3

Road Network and Damaged Buildings in Urban Areas: Short and Long-term Interaction

A. GORETTI[1,*] and V. SARLI[2]
[1]*National Seismic Survey, Civil Protection Department, Via Vitorchiano 4, 00189 Rome, Italy;* [2]*DiSGG, University of Basilicata, C.da Macchia Romana, 85100 Potenza, Italy*
Corresponding author, Tel: +39-06-68204226, Fax: +39-06-68202877, E-mail: Agostino.Goretti@protezionecivile.it

Received 27 July 2005; accepted 3 January 2006

Abstract. In this paper, a model able to analyse the seismic behaviour of road network in urban areas, considering interaction between buildings and roads is presented. Damage to buildings and short-term countermeasures, such as propping, can affect roads and even block them, reducing capacity of the road network. Two successive phases are considered. In the first, immediately after the seismic event, emergency services have to reach the relevant buildings. Here, the network topology is of interest. In the second, in the long term, network capacity is not yet completely restored and network demand has to account for displaced people due to unusable buildings. In this case, road serviceability is of interest. In order to consider uncertainties on building behaviour, a probabilistic approach is developed and the network is analysed by means of Monte Carlo simulation. The methodology is applied to the municipality of Potenza (southern Italy) evaluating in the short term, the probability of strategic buildings are not connected and, in the long term, road serviceability.

Key words: building vulnerability, emergency, road network, road serviceability

1. Introduction

Due to its vital role in case of emergency and in normal life conditions, more and more attention has been paid to seismic road network analysis. Recent approaches (SERGISAI, 2001; Menoni *et al.*, 2002; Franchin *et al.*, 2006; UNIBAS-SSN, 2003; Goretti, 2004) differ on the level of the analysis (urban, regional or national) and on the qualitative or quantitative description of the network behaviour. In general, road network demand and capacity vary in time, depending on the physical damage suffered, elements at risk and restoration policies. In the first phase, collapsed buildings can alter road capacity and even block roads so emergency services, such as fire and ambulance, cannot get through and relevant buildings, such as schools, cannot be accessed. If the evacuation is not controlled, mobility demand on the road network is difficult to define. In the second phase (restoration), emergency countermeasures, such as propping, and incomplete debris removal still reduce road capacity while displaced people, due to unusable buildings, alter demand on the road network. A change in both road capacity and mobility demand implies a change in road service level, expressed as the ratio between traffic flow and road capacity (Transportation Research Board, 1985).

Prior to the seismic event, a road serviceability analysis relies on the interaction between mobility demand (traffic flow), road capacity and territory (Kanafany, 1983). After the earthquake, a rigorous approach should consider both the vulnerability of road network, that reduces road capacity, and several interacting urban sub-systems, that modify road demand. Since a quantitative evolutionary model of the whole urban system is nowadays almost impossible, in the present paper the interaction analysis will be limited to following specific items: road network and residential buildings.

Road serviceability due to building seismic behaviour may depend on several items: building vulnerability, collapse mechanisms, width of roads, distance between buildings' façades road, and height of buildings. Building height is related to the debris quantity and to their extension, and to the geometry of short-term countermeasures, such as propping. The width of the road and the distance between building face and road, including sidewalks, are important parameters to estimate the road functionality in relation to the area occupied by the generated debris or by propping. All these parameters are related to the type of urbanization (Argyroudis *et al.*, 2003).

Immediately after an earthquake only debris is present on the roads, while, as time passes, debris is removed and, if necessary, propping and other kinds of short-term countermeasures are put in place. Therefore, road vulnerability depends on impact, but also varies with time depending on restoration activities.

In the paper, a model able to evaluate road vulnerability is presented. In order to consider uncertainties on building behaviour, a probabilistic approach is developed and the network is analysed by means of a Monte Carlo simulation. Short-term and long-term interactions are both considered. The methodology is then applied to the urban area of Potenza (southern Italy) evaluating the probability that strategic buildings are not connected (phase I) and the probability of exceeding a specified road service level (phase II). Main results are highlighted and discussed.

2. Seismic road vulnerability in urban area

In the context of urban area, road blockages are mainly due to indirect damage than to direct damage (HAZUS, 1997). More specifically, road blockages are considered to be caused only by building damage, disregarding other causes of failure, such as ground failures and bridge collapses (Argyroudis *et al.*, 2003). Seismic road vulnerability is estimated following the methodology developed initially by Goretti (2004, 2005), that will be summarised. The road network is represented by a graph with nodes and links (roads), the latter are associated to roads. A binary behaviour is assumed for each road, where the two possible states are: $S = 0$, if the road is accessible, and $S = 1$ otherwise. Since it is not certain what will happen in case of an earthquake, the state of the road will be considered a random variable, requiring a reliability analysis of the network.

If the number of blockages along each road follows a Poisson distribution, the road failure probability conditional on seismic intensity I, P_{f}, is given by:

$$P_{\mathrm{f}} = 1 - \mathrm{e}^{-N_{b|I}} \tag{1}$$

where b stands for blockage and $N_{b|I}$ is the mean number of blockages when intensity I affects the road. To evaluate $N_{b|I}$ detailed data for each building facing each road of the urban area should be available. As this is not always the case, recourse is made to an approach in terms of classes of structures. Denoting by N_{bld} the total number of buildings along the road sides, then the mean number of blockages can be given by:

$$N_{b|I} = N_{\mathrm{bld}} P(b|I) = N_{\mathrm{bld}} \sum_{T} P(b|T, I) P(T) \tag{2}$$

where $P(b|I)$ is the probability that a building will block the road when affected by intensity I, $P(b|T, I)$ is the same probability in case of a building of vulnerability class T and $P(T)$ is the distribution of buildings in vulnerability classes along the road. Each building can block the road depending on its degree of damage, on activated failure modes and on inserted short-term countermeasures.

Damage will be assumed as a discrete random variable ranging from 0, the null damage, to 5, the total collapse, as stated in recent macroseismic scales, such as the EMS '98 (Grunthal, 1998). As possible causes of road failure p=propping, o=partial collapse due to out of plane wall overturning and c=total collapse will be considered (Figure 1). An index k, ranging as k =p,o,c will then be introduced. Also note that events p, o and c are mutually exclusive, as they depend on different damage levels. Hence we have:

$$\begin{aligned} P(b|T, I) &= \sum_{k=\mathrm{p,o,c}} P(b|k, T) P(k|T, I) \\ &= \sum_{k=\mathrm{p,o,c}} \sum_{d=0,..,5} P(b|k, T) P(k|d, T) P(d|T, I) \end{aligned} \tag{3}$$

Figure 1. Examples of road blockage due to (i) out of plane wall overturning in masonry buildings (Marche 1997, Italy), blockage type o, (ii) heavy damage to RC concrete building (Athens 1999, Greece), blockage type c, and (iii) short-term countermeasures in masonry building (Molise 2002, Italy), blockage type p.

The term $P(k|d, T)$ represents the probability that in a building of type T, suffering damage grade d, a propping is inserted, or an out of plane partial collapse or a total collapse occurs. $P(b|k, T)$ is the probability to have a road blockage when a propping is inserted, or a partial or total collapse occurs in a building of type T and it depends on building and road geometry. It will be then called "geometric effect". $P(d|T, I)$ is the building primary vulnerability, expressing the probability that building type T suffers damage grade d, when affected by intensity I. The summation $\sum_{k=\mathrm{p,o,c}} P(b|k, T)P(k|d, T)$ represents the secondary vulnerability, that is the probability of road blockage when building type T experiences physical damage d. Being damage a discrete variable, as well as building type and causes of road blockage, all the above terms are matrices. Matrices $P(k|d, T)$ and $P(d|T, I)$ are evaluated on the basis of statistical analysis on recent Italian post-earthquake surveys and are reported in Goretti (2004). For $P(b|k, T)$, we resort to geometric considerations on failure modes and short term countermeasures.

The model requires to determine the number of buildings alongside any road. It can be obtained from a detailed survey, from maps or, more easily, if available, from a geographical information system (GIS). Alternatively it can be evaluated from the percentage of built road length, α_{ed}, and from the mean building length, b_{bld}:

$$N_{\mathrm{bld}} = 2L\alpha_{\mathrm{ed}}/b_{\mathrm{bld}} \tag{4}$$

where L is the road length and the factor 2 accounts for the two sides of the road (see application).

The validity of the assumption of Poisson distribution for road failure is limited to almost independent building blockages. This is often confirmed by post-earthquake damage observation. However, when full or strong correlation exists among building blockages, a different assumption should be introduced and the road failure probability can be assumed as the minimum building blockage probability along the road.

3. Road network functionality analysis in urban area: short term

Immediately after an earthquake two mobility traffic components can be considered: evacuation mobility and service mobility. The former refers to private vehicle flows and it is very difficult to estimate, unless an evacuation plan has been enforced. The latter refers to emergency vehicle flows. Sometimes, emergency plans assume emergency vehicles are the only ones allowed to move along roads, because people evacuating are forced to move on foot. In this case it is possible to assume an empty road network and, hence, road network connectivity between strategic and/or relevant buildings is of main interest in this phase.

A reliability analysis of the network model is performed taking the blockage probability in each road into account. Several multiple objective functions are evaluated, according to specific needs of the end-users. For example, access to every school by fire and ambulance services and by at least one road in the urban area, etc. Though road blockages can be considered independent, path-sets are to be considered dependent, since more than one path-set can include the same road. The reliability analysis of the network is then performed by means of a Monte Carlo simulation, randomly generating several damaged networks from the original one, including or excluding each road according to its failure probability. For each generated network, the network connectivity is checked with a non-recursive algorithm (Leestma and Nyhoff, 1993). At the end of the analysis, statistics on results give the failure probability of the selected objective functions.

4. Road network functionality analysis in urban area: long term

In the long term, road serviceability analysis requires evaluation of interaction between mobility demand (traffic flow), road capacity and territory (Kanafany, 1983). As in short term, road capactiy will be again represented by means of a graph, with nodes and connection roads; however in this case every road is characterised by its own capacity. Mobility demand is usually represented by means of a matrix named inter-exchange matrix or origin–destination-matrix, M_{OD}, (Kanafany, 1983) in which its generic element $M_{\mathrm{OD}}(i, j), (i, j = 1, \ldots, N_{\mathrm{Z}})$, represents the number of vehicles in a time interval that move from ith origin to the jth destination, once the case study area is divided into N_Z zones.

Several models are available to evaluate M_{OD} in normal conditions. However, after an earthquake, buildings can be unusable due to heavy structural and non-structural damage and, hence, people have to be displaced. Recovery areas are usually established within the urban emergency plan. From a conventional seismic scenario it is then possible to evaluate, in each urban zone, the number of displaced people and their possible new location. The same models used to evaluate M_{OD} in normal life can then be used to evaluate M_{OD} after an earthquake. The emergency plan is then an important ingredient to obtain a realistic demand on the road network after the earthquake. If the emergency plan is not available, reasonably assumptions on recovery areas have to be made.

Because matrix M_{OD} represents vehicle flows between zones, in order to evaluate traffic flow into each road, flow allotment procedure should be developed. In the present study, a deterministic methodology to allot flows has been used. This is based on the idea that each driver will be able to evaluate generalised transport costs (represented by travel time, path length, etc) associated to several paths, and that he will choose the path that minimises the transport cost. In the following, for sake of simplicity, the generalised cost has been assumed proportional to the length of the path, and hence, an allotment algorithm has been developed to search for the shortest path, with the constraint that road capacities can not be exceeded.

In more detail, given the road network graph $G(A, N)$, a value b_i (named balance of node) is associated to ith node belonging to the nodes set, N. If $b_i = 0$, the node is a crossing node; if $b_i > 0$, the node is a source or origin; if $b_i < 0$, the node is a destination. Similarly, a unit cost on flow, c_{ij}, and capacity, u_{ij}, are associated to each arc with extremes i and j belonging to the arcs set A (Figure 2). Flow on each arc, to be determined, is named x_{ij}. The mathematical formulation can be expressed as:

– Capacity bound of every road arc: $0 \leq x_{ij} \leq u_{ij} \quad \forall (i, j) \in A$,
– Flow storage bound of every node:

$$\sum_{(i,j)\in \mathrm{FS}(i)} x_{ij} - \sum_{(j,i)\in \mathrm{BS}(i)} x_{ji} = b_i, \quad \forall i \in N \tag{5}$$

– Objective function: $\min(\sum_{i,j} c_{ij} x_{ij}) \quad (i, j) \in A$

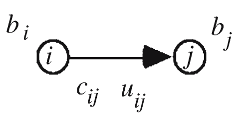

Figure 2. Attributes of road network arcs.

where FS is the forward star of flows and BS is the backward star of flows. Denoting by **E** the nodes/arcs matrix that characterises the network topology, **b** the balances vector, **c** the costs vector and **u** the capacities vector, the flow allotment is solved as $\min(\mathbf{c}^T\mathbf{x})$ subjected to the constraints $\mathbf{Ex}=\mathbf{b}$ and $\mathbf{0} \le \mathbf{x} \le \mathbf{u}$.

In order to consider the restoration on the road network functionality, debris and short-term countermeasures removal are assumed to be of exponential type $R(t) = \exp(-\lambda t)$ where the λ parameter is evaluated supposing that after 6 months 30% of the short-term countermeasures and 80% of the debris are removed. The resulting time evolution is reported in Table I. From these values, probabilities of road blockages are evaluated. Starting from the blockage probability in each road, several networks are then generated through Monte Carlo simulation as in short-term analysis. For each generated road network an assignment procedure is implemented and the road service level obtained. Statistics over all the simulated networks give average values of service levels and/or probability to exceed a given service level.

5. Application

The above methodology is applied to the urban area of Potenza (southern Italy, 70,000 inhabitants). Data on building vulnerability, road network and road geometry, have been obtained from the so called "Potenza Project" (UNIBAS-SSN, 2003) and completed, when necessary, with an appropriate survey. The Potenza road network graph is presented in Figure 3. It consists of 331 links and 227 nodes.

The urban area has been subdivided into seven homogeneous macrozones with respect to main activities performed and type of urbanisation (Figure 4, right). Macrozones 1, 2, 3, 4, 6 and 7 are residential ones including all the essential services, while macrozone 5 is an industrial one. Macrozone 7 is the historical core. Macrozones 2 and 3 are entirely built since the 70s, macrozones 1 and 6 are partially built since the 80s, macrozone

Table I. Assumed recovery time evolution

Days	Presence of propping (%)	Presence of debris due to partial and total collapses (%)
30	95	80
90	85	45
180	70	20
365	45	4

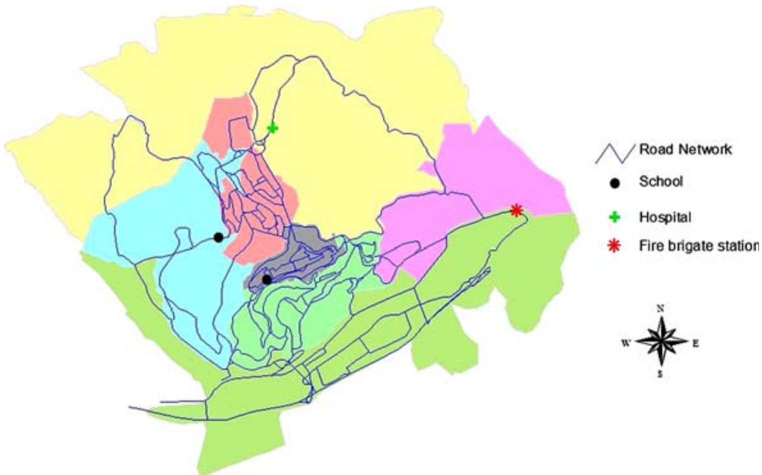

Figure 3. Potenza road network graph, and a part of emergency system (Hospital=+, Schools=•, Fire Brigade Station=*).

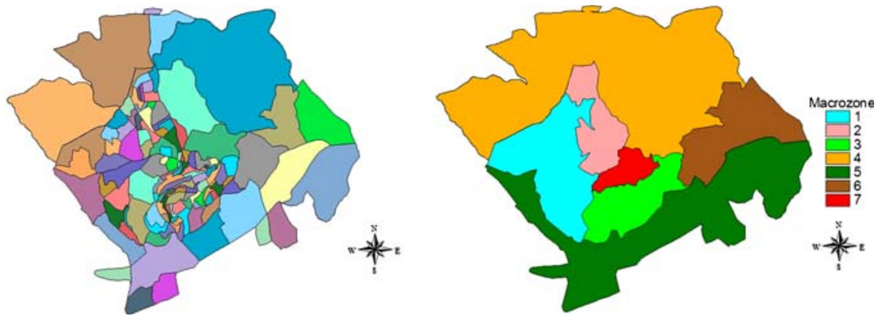

Figure 4. Potenza urban area: (left) Istat census tracks and assumed subdivisions into seven macro-zones (right). Residential zones partially built= 1 and 6; Residential zone entirely built= 2 and 3; New residential zone= 4; Industrial zone = 5; Historical centre= 7.

4 is an expansion area since the 90s. Since each macrozone is characterised by similar building age and since the distance between the building face and the road is related to the type of urbanisation of each area (Argyroudis *et al.*, 2003), we assumed a constant building vulnerability distribution and a constant H/L ratio within the same macrozone.

Data on building vulnerability were available in the form of distribution of vulnerability classes $P(T)$ on Istat census zones (Figure 4, left). Building distribution in vulnerability class, $P(T)$, within the seven macro-zones are then obtained by making a weighted average of the Istat Census zone $P(T)$ values. Results are reported in Table II, where letters A, B, C and RC

Table II. Distribution of building vulnerability in each macro-zone; A, B, C, RC=Typology of buildings

Macro-zones	Distribution of vulnerability class			
	P(A)	P(B)	P(C)	P(RC)
1	4.7	4.8	32.9	57.6
2	3.3	8.1	64.3	24.4
3	5.4	4.3	57.1	33.2
4	1.7	4.2	15.6	78.5
5	5.8	11.9	38.1	44.3
6	10.2	12.8	44.9	32.1
7	16.5	5.0	44.2	34.3

refer to the following building constructional typologies: Masonry of poor, medium and good quality and reinforced concrete.

Building height-road width ratio (H/L) is reported, for each macro-zone in Table III, together with the mean building length, b_{bld}, and the range of number of stories, N_s. In addition, the percentage of built road length α_{ed} is evaluated, for every road of the graph, by visual inspection on the map of Potenza.

Starting from data in Table II and Table III, blockage probability of every road is evaluated for macro-seismic intensity I_{MCS}=VIII-IX, applying the above described methodology. Results are reported in Figure 5. Almost 150 links over 331 have a null blockage probability, either for absence

Table III. Road and building geometry data in each macro-zone; H =building height; L =distance between building face and road; b_{bld} =mean building length; N_s =number of stories

Macro-zones	Road and building geometry				
	$(H/L)_{max}$	$(H/L)_{min}$	b_{bld}	$N_{s,max}$	$N_{s,min}$
1	3.3	2.0	25	13	2
2	3.6	0.7	24	6	2
3	4.0	1.2	24	8	1
4	1.7	0.8	25	6	1
5	2.0	1.5	30	5	1
6	3.0	1.5	20	5	2
7	5.0	1.0	20	11	1

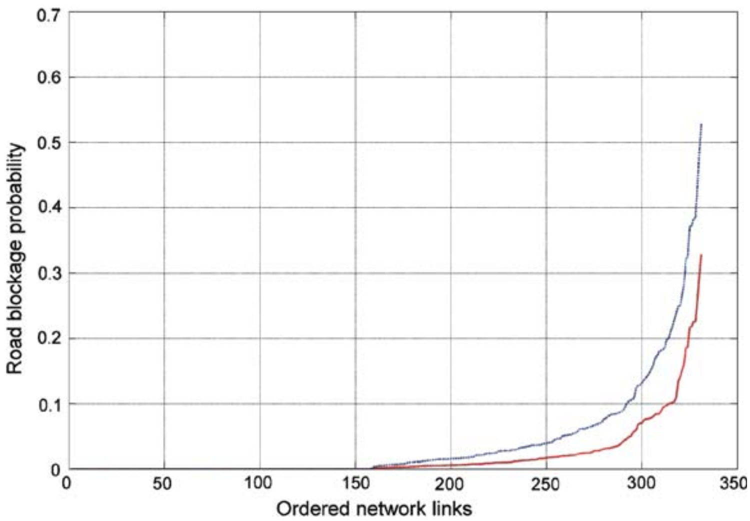

Figure 5. Road blockage probability on the network for I=VIII-IX MCS. Continuous line: only presence of debris, dash-dot line: debris and short term countermeasures.

of buildings at sides or for low H/L ratios. Maximum road blockage probability is about 0.32, when only debris block the roads, and about 0.53 in case of presence of emergency countermeasures and debris. The average value, over the entire network, of blockage probability is 2% and 4%, respectively, in case of absence or presence of short-term countermeasures.

In order to verify the reliability of the methodology used to evaluate road blockage probability from rough data, three roads characterised by different building vulnerability distributions and geometry ratios, Via Ciccotti, Via Lazio and Via Mazzini, are considered in detail. Geometry and vulnerability are surveyed for every building of each road. The blockage probability is then evaluated considering, for each road, the actual joint vulnerability and geometry. Comparison of the blockage probability obtained with the macro-zone approach, in which independence of H/L ratio from building vulnerability was assumed, and with the detailed analysis is reported in Figure 6. At least for two roads, a substantial agreement between the two analyses is found.

The short-term network connectivity is first analysed. In Figure 3 two primary schools (•), one in the historical core and the other outside, the Fire Brigade Station (*) and the Hospital (+) are located on the road graph. Starting from the road blockage probabilities, Monte Carlo simulation (7,000–10,000 simulations) on the network connectivity provides results reported in Table IV, for intensity I_{MCS}=VIII-IX and I_{MCS}=IX-X, and in absence or presence of short-term countermeasures. The two schools appear to be in a very different condition. The one located in periphery

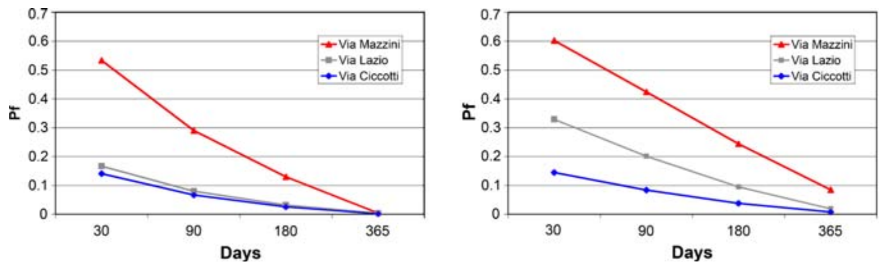

Figure 6. Blockage probability on Via Ciccotti, Via Lazio and Via Mazzini obtained (left) from macrozone analysis and (right) from detail survey of each building.

Table IV. Probability of disconnection between primary schools and Fire Brigade Station (FBS) and Hospital (H)

	I =VIII-IX MCS		I =IX-X MCS	
	Only debris	Debris and short term countermeasures	Only debris	Debris and short term countermeasures
FBS-School 1	0.192	0.435	0.789	0.931
FBS-School 2	0.000	0.000	0.0004	0.0016
H-School 1	0.196	0.442	0.790	0.930
H-School 2	0.000	0.000	0.0003	0.0017

(School 2) will seldom disconnect with respect to the Fire Brigade Station or the Hospital, at least for the investigated intensities. This is due to wider roads and a less urbanised context. On the contrary, the school located in the historical centre (School 1) has a substantial chance to be not connected both from the Fire Brigade Station or the Hospital. This is mainly due to the geometric effect (Goretti, 2004), since in that area buildings can have up to 6–7 stories facing 2 lane roads, with narrow or non-existent sidewalks. The case of propping on the network is quite unrealistic, because in the early days short-term countermeasures are not yet in place. However, it gives an idea of the relative influence of debris and propping on the network connectivity. In comparison to debris, the propping effect decreases for increasing intensity, since the number of collapsed buildings increases. The above results are obtained considering one-way roads and show a very high probability of disconnection for School 1 and for intensity I=IX-X MCS. Allowing flows in both direction in every road (also one-way roads), as will likely occur in an emergency, blockage probabilities reduce to more realistic values: between School 1 and Fire Brigade Station, for I=VIII-IX MCS, in case of only debris present $P_{\mathrm{disc},d}$=0.0013 and also considering short-term countermeasures $P_{\mathrm{disc},d+s}$=0.0234, while for I=IX-X MCS $P_{\mathrm{disc},d}$=0.186 and $P_{\mathrm{disc},d+s}$=0.450, respectively. It appears, as in a previous application (Goretti, 2005), that the loss of connection becomes relevant only for high intensity, as above I=IX-X MCS. Obviously, results strongly depend on location of strategic and relevant buildings and on roads network and vulnerability. Hence they cannot be generalised to other situations, although they sound reasonable for most of relevant buildings located in any historical centre.

Interaction at long term and network serviceability is investigated next. Post-earthquake M_{OD} is evaluated with respect to the seven selected macro-zones, considering the people displaced into the recovery areas reported in the Municipality emergency plan. The number of homeless in each census track was estimated through a standard seismic scenario, for I=VIII-IX MCS. Resulting M_{OD} is reported in Table V.

Time restoration reported in Table I is used to evaluate the time evolution of the road blockage probability in every link of the network, again for I=VIII-IX MCS. Average values over the whole network are reported in Table VI. Starting from the road blockage probabilities, Monte Carlo simulation is repeatedly performed at time t=30, 90, 180 and 365 days from the event. While the probability of road blockage reduces significantly in one year, MOD matrix is assumed constant, since, according to the Italian experience, in one year the number of buildings that have been repaired is negligible, having then almost the same number of displaced people. For each simulation the capacity of each link is reduced depending on its blockage probability and the flow assignment problem solved. Service level of each link, representing the saturation grade of the link, is then evaluated as ratio of demand and capacity flow. Table VII shows the average value over the whole network of the road service level. Service level decreases in time, since road blockage probability decreases and vehicle flow can distribute on a larger

Table V. M_{OD} including displaced people due to unusable buildings. Cell (I, J) represents number of vehicles per hour from origin I to destination J

	1	2	3	4	5	6	7
1	0	348	521	261	214	105	42
2	207	0	248	157	390	81	275
3	219	488	0	723	522	279	353
4	326	736	1318	0	746	405	289
5	344	425	1163	495	0	396	367
6	140	66	468	76	144	0	31
7	67	124	404	482	284	66	0

Table VI. Average value of the road blockage probability over the network (I=VIII-IX MCS)

Days	Average road blockage probability
30	0.0297
90	0.0143
180	0.0057
365	0.0009

Table VII. Average value, standards deviation and coefficient of variation of the service level over the network

Days	Average	Std.Dev	CoV(%)
30	0.2681	0.318	118
90	0.2681	0.335	125
180	0.2595	0.350	135
365	0.2595	0.361	139

number of roads. The small time variation of the average service level value is due to network redundancy and to the fact that many roads are still operational and their service level does not vary.

Although the average value of the service level does not vary too much in time, and with respect to the quasi normal-life condition (absence of blockages, but including in M_{OD} the effect of displaced people), this does not mean that all the roads experience the same service level. This is highlighted at Via Vaccaro, selected for its importance in the road network. Figures 7 and 8 respectively show the time evolution of Via Vaccaro blockage probability and the time evolution of its service level. It appears an unacceptable service level just after the earthquake that decreases as time goes by. It is also interesting to report (Figure 9) the cumulative distribution function (CDF) of the service level on Via Vaccaro at 30, 90, 180, 365 days from the event. From the curves, the probability of exceeding a given service level on the road can be evaluated at different days from the event. In particular there is about 20% of probability that Via Vaccaro saturates its capacity at 30 days from the event. Note also that, as time passes, the CDF is more and more steep around the service level of quasi-normal life condition, SL=0.22. Asymptotically, the service level is going to behave as a deterministic variable, as consequence of the assumed deterministic flow assignment. However, at one year from the event the mean value of

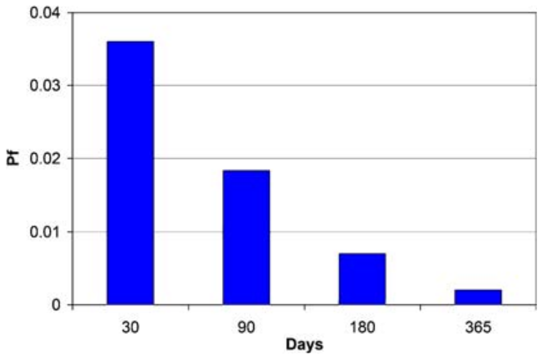

Figure 7. Time evolution of the blockage probability on Via Vaccaro.

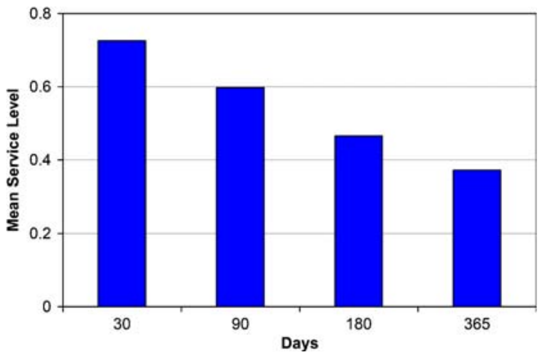

Figure 8. Time evolution of the mean value of service level on Via Vaccaro.

the service level (Figure 8) can still differ significantly from the median value (Figure 9).

Road blockage probabilities and road service levels have also been analysed within the seven macro-zones. Results, not reported here, show that macro-zones with higher road blockage probabilities are not necessarily the ones with higher service levels, because road service level is also influenced by other factors, such as flows going to and from the zone, transit flows through the zone, and redundancy of the zone network.

6. Conclusions

In this paper a probabilistic methodology able to handle the short and long-term post-earthquake functionality of road network in urban areas has been proposed. The analysis has been limited to interaction of road network, residential buildings and emergency services on network service level. As possible causes of road blockage, seismic countermeasures on buildings, as well as building partial and total collapses, has been introduced. In order to consider uncertainties on building behaviour, a

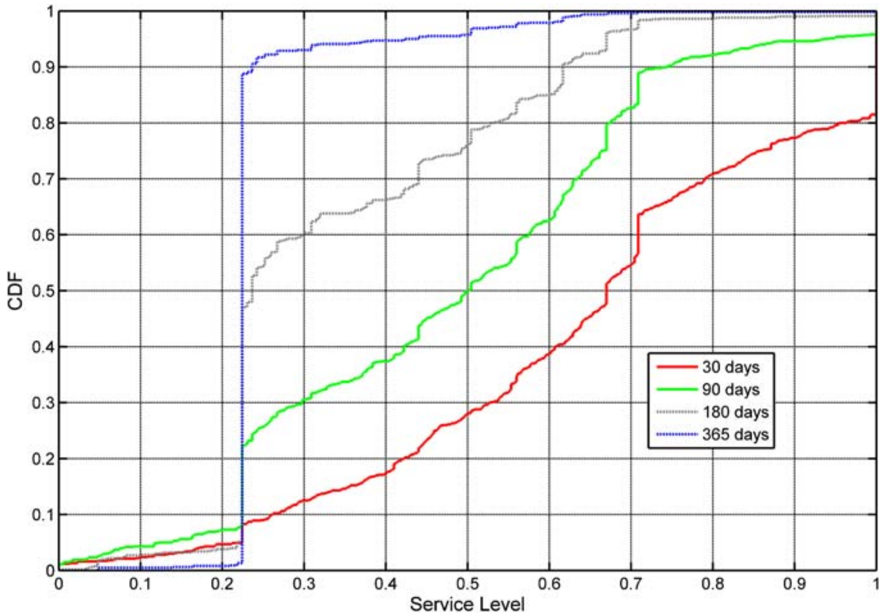

Figure 9. Time evolution of the cumulative distribution functions (CDF) of service level on Via Vaccaro.

probabilistic approach has been developed, and the network analysed by means of a Monte Carlo simulation.

In the short term following the event, the network topology is of primary interest in order to evaluate whether emergency vehicles can or cannot reach strategic and relevant buildings. In the long term following the event, the service level of the network is of primary interest to check the network functionality.

The proposed methodology has been applied to the urban area of Potenza (southern Italy). With reference to this application, the following conclusions can be drawn in the short term:

- The interaction among road network, buildings and emergency services is significant only for seismic intensities higher than I_{MCS}=IX-X. For smaller intensities, the limited number of heavily damaged buildings makes the problem negligible;
- The presence of propping can significantly increase the probability of road blockage. The increase reduces as seismic intensity increases;
- The probability of disconnection is significant for buildings located in the historical centre, since streets are narrow and buildings more vulnerable.
- There is a need, in order to reduce the blockage probability, to allow emergency vehicle flows in both directions, even on one-way roads. This calls for special post-earthquake road signs.

In the long term, the following conclusions can be drawn.

- Since road blockage probability decreases in time, the number of blocked roads decreases and vehicle flows can distribute on a larger number of roads. For this reason, roads are less saturated as time passes from the seismic event.
- Network redundancy and continuously operational roads can lead to small variation of the service level averaged over the whole road network.
- However, for an individual road, the mean value of the service level just after the earthquake can be significantly greater than the service level in quasi normal-life conditions. Roads can even saturate. CDF of the service level can provide the probability of exceeding a given service level.
- Within macro-zones, the dependence of the service level on road blockage probability is not straightforward; others factors are dominant, such as flows going to and from the zone, transit flows through the zone, and redundancy of the zone network.

The proposed methodology allows us to recognize the most vulnerable and the most saturated links of the network, providing useful information in an optimal post-earthquake and normal life urban area planning.

References

Argyroudis, S., Momge, O., Finazzi, D. and Pessina, V. (2003) Vulnerability assessment of lifelines and essential facilities (WP06): methodological handbook – Appendix 1: Roadway transportation system, Risk-UE Final Report, Report n° GTR-RSK 0101-152av7, February.

Franchin, P., Lupoi, A. and Pinto, P.E. (2006) On the role of road network in reducing human losses after earthquakes. *Journal of Earthquake Engineering*, WSPC Journals, 10(2), 195–206.

Goretti, A. (2004) Interaction between urban system components: road network, buildings, emergency system. *XI National Congress on Seismic Engineering*, Italy, Genoa, 25–29 January, SGE Editoriali, Padova, Italy (in Italian).

Goretti, A. (2005) A probabilistic model able to handle interaction among road network, buildings and emergency services in urban areas. *Proc. IX International Conference On Structural Safety And Reliability, ICOSSAR'05*, Rome, 19–23 June.

Grunthal, G. (1998) European Macroseismic Scale 1998, Cahiers du Centre Eur. de Geodyn. et de Seism., v. 15, pp. 1–99.

HAZUS99-SR2 (1997) *Technical Manual*, Chapter 7 "Direct physical damage to lifelines – transportation systems", FEMA Distribution Center, Maryland, 97 pp.

Kanafany, A. (1983) *Transportation Demand Analysis*. Mc Graw-Hill, New York.

Leestma, S. and Nyhoff, L. (1993) *PASCAL Programming and Problem Solving*. Macmillan, USA.

Menoni, S., Pergalani, F., Boni, M.P. and Petrini, V. (2002) Lifelines earthquake vulnerability assessment: a systemic approach. *Soil Dynamic and Earthquake Engineering*, Elsevier Science, Vol. 22, pp. 1199–1208.

SERGISAI (2001) Seismic risk evaluation through integrated use of geographical information systems and artificial intelligence techniques, Project ENV4-0279, Final report, DGXII, EC.

Transportation Research Board (1985) *Highway Capacity Manual*. Washington.

UNIBAS-SSN (2003) Seismic risk evaluation of Potenza urban system. Potenza Project, II Part. Final report (In Italian).